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## ***Final Report: NAG5-9576***

### ***“The Diversity of Martian Volcanic Features as Seen in MOC Images and MOLA Topographic Data”***

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## 1. Objectives of Completed Research

This project focused on the evolution of the summit areas of Martian volcanoes. By using data collected from the Mars Orbiter Camera (MOC) and Mars Laser Altimeter (MOLA) instruments, we tried to better understand the diversity of constructional volcanism on Mars, and hence further understand eruption processes. We investigated the styles of volcanism on the major volcanic constructs (Olympus, Arsia, Pavonis, and Ascraeus Montes), and also studied the role of magma-volatile interactions within the shallow subsurface of these volcanoes and the surrounding areas. Theoretical models for internal processes within volcanoes, including the thermal influences of dike intrusions on pre-existing volatiles, were developed based on our identification of landform distributions.

Volcanism represents one of the major geologic processes that have shaped the surface of Mars (Greeley and Spudis, 1981), and the new data being collected by Mars Global Surveyor (MGS) provide an unprecedented new opportunity to investigate the range of activity in space and time. Relating geologic observations to theoretical models is one of the prime objectives of the Planetary Geology and Geophysics Program, and so our work directly relates to this goal. By focusing our investigation on the role of volatiles as they may affect explosive volcanism, we hoped to enhance the community's knowledge of the distribution of water and ice on Mars during the recent geologic past. By "following the water" on Mars, our work is of relevance for future site selection and for the interpretation of imaging spectrometer data that show hydrothermal alteration of surface materials (e.g., within volcanic craters or the walls of the large canyons). Our calculations of eruption conditions were based on present day atmospheric conditions, so that we took the approach that if we were unable to adequately model the observed landforms this may be an indication that some property of the atmosphere (particularly the density) has changed.

Volcanism on Mars probably continued into the recent geologic past; indeed initial analysis of MOC data even suggests that volcanism could continue until the present (Hartmann, 1999). A number of young volcanic landforms appear to have formed by the interaction between subsurface volatiles (water and/or ice) and subsurface magma (e.g., see review by Chapman et al., 2000). Gaining a greater understanding of the distribution of volatiles on Mars, and how local heat sources may have remobilized water or ice within the crust, has important implications for the present day distribution of volatiles on Mars. Through our study of the landforms, which appear to result from the interaction of intrusions and subsurface volatiles, we hoped to be able to better quantify the volumes of volatiles involved. We tried to provide new information on their distribution as a function of depth beneath the surface, their rate of release following an intrusion, and the physical properties of the country rock. All of these factors have considerable relevance to future NASA missions to Mars (both orbital and lander missions), as they relate directly to the potential for hydrothermal activity on Mars, and the resultant implications this has for biological habitats.

Our work provided new insights into the diversity of volcanism on Mars, and the distribution of Martian volatiles in space and time. Highlights of our results include: (1) the identification of large ash deposits at the summit of Arsia Mons (Mouginis-Mark,

2002); (2) the study of a large flank eruption on Elysium Mons (Wilson and Mouginis-Mark, 2001) and the estimation of the effusion rate needed to produce the observed lava channel; (3) the quantitative description of dike intrusion into volatile-rich terrain to explain the origin of Hrad Vallis (Wilson and Mouginis-Mark, 2003a); (4) the identification of constructional ridges on top of very young lava flows from Olympus Mons, with the interpretation that these ridges were formed by very recent phreatomagmatic eruptions (Wilson and Mouginis-Mark, 2003b); and (5) the characterization of the dimensions and slope distributions on 18 volcanic edifices on Mars (Kallianpur and Mouginis-Mark, 2001).

Central to the work was the development of numerical models to explain the detailed morphology of features seen in the MOC data and the MOLA topographic information. These models were in turn based on parametric data (depth and width of depressions, existence of possible dikes on the floors of graben, and spatial distribution of materials surrounding the depressions) collected from MOC and MOLA data. We used our most recent re-assessments of the factors controlling the sizes, shapes and locations of volcanic intrusions on Mars (Scott & Wilson, 1999, 2002; Scott et al., 2002; Wilson & Mouginis-Mark, 2001, 2003a; Wilson & Head, 2000, 2001) to provide the inputs to calculations of the way the internal structure and the process of magma ascent controls the morphology of the summit area and the adjacent regions.

We also studied volcano edifices, where intrusions close to the summit may have released volatiles. In particular, we identified an extensive area of fine materials, interpreted to be the products of explosive volcanism, close to the summit of Arsia Mons (Mouginis-Mark, 2002) (Fig. 1). We studied the geomorphic characteristics of the possible source areas of these deposits and to model the range of possible explosive eruptions that generated them. Theoretical models for internal processes within volcanoes, especially the roles of dike and sill intrusion, were developed based on our identification of the scales and locations of the resulting landforms (Wilson and Mouginis-Mark, 2003b).

Many of the morphological data that we collected during this investigation were also used in the quantification of volcanic processes on Mars. Fundamental volcanic processes on Mars, and the internal structures of the resulting volcanic systems, generally mimic those on Earth. Thus, shield volcanoes have multiple generations of sub-summit magma reservoirs evidenced by the presence of collapse calderas (Crumpler et al., 1996; Scott and Wilson, 1999; Wilson et al., 2001), summit eruptions occur due to near-vertical dike migration to the surface (Wilson and Mouginis-Mark, 2001), rift zones are formed by lateral dike injection and flank eruptions occur from points along those rift zones (Crumpler and Aubele, 1978), and shallow sills form from the distal parts of rift zone dikes (Scott and Wilson, 1999). On the larger scale, mantle plumes appear to have fed magma laterally into giant dike swarms which approached close enough to the surface to produce swarms of graben radial to the plume center (Scott et al., 2002; Wilson and Head, 2002); some of these graben contain rimless craters caused by collapse after gas release, dike roof stoping or possibly sustained local eruptions (Scott and Wilson, 2002). Elsewhere, giant regional dikes appear to have injected shallow sills that interacted with the cryosphere, in at least one case causing a major phreatomagmatic explosion (Wilson and Mouginis-Mark, 2003a). The above evidence, together with theoretical appraisals of

volcanic processes on Mars (Wilson and Head, 1994; Head and Wilson, 2002), suggests that only a relatively small number of geometries needed to be considered in order to model these eruption or intrusion scenarios and their consequences.

The results from this grant include a greater understanding of the temporal and spatial variations in the eruptive history of volcanoes on Mars, and the impact of this activity on the volatile inventory within the top few kilometers of the crust. These results pertain to the availability of volatiles (both juvenile magmatic volatiles and ground water contained within the near-surface rocks) and to magma supply rates at appreciable distances (tens to hundreds of kilometers) from the centers of volcanoes. Both of these aspects are intimately connected to large-scale crustal evolution and to the temporal distribution of volatiles across the planet (McKenzie and Nimmo, 1999). Explosive volcanism on Mars, a major factor in the release of water at the surface, may have been driven not only by volatiles within the parental melt, but also by magma encountering water or ice at shallow depth (Mouginis-Mark et al., 1982; Crown and Greeley, 1993; Robinson et al., 1993). The depth of this permafrost layer is not known with certainty, but Squyres et al. (1992) have estimated the mid-latitude thickness to be ~2 km. Our work on the origin of Hrad Vallis (Wilson and Mouginis-Mark, 2003a) helped to refine this depth estimate.

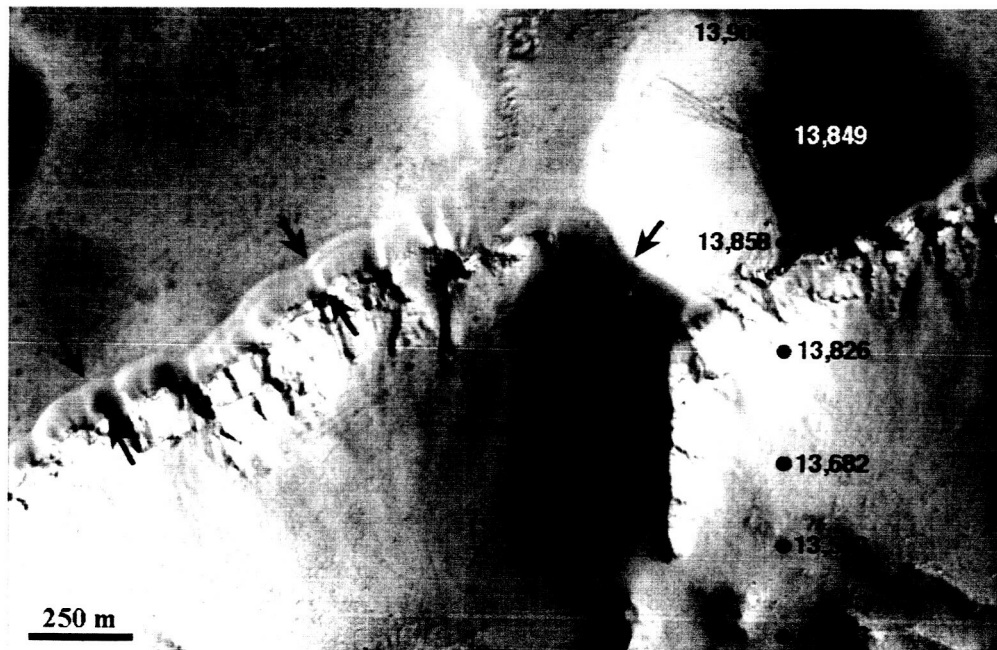


Figure 1: An extensive layer of material (between arrows) covers parts of the summit of Arsia Mons (Mouginis-Mark, 2002). MOLA data (elevations at right are in meters) allow the layer to be estimated as being 45 - 50 m thick), indicating that this is not an eolian deposit.

## 2. Resulting Publications

The results from this grant are described in the following publications (6 papers and 12 abstracts):

*Papers published:*

- Wilson, L. and P.J. Mouginis-Mark (2001). Estimation of volcanic eruption conditions for a large flank eruption on Elysium Mons, Mars, *J. Geophys. Res.* 106: 20621 - 20628.
- Mouginis-Mark, P. J. (2002). Prodigious ash deposits near the summit of Arsia Mons volcano, Mars. *Geophysical Research Letters* 29: 10.1029/2002GL015296.
- Scott, E.D. & Wilson, L. (2002). Plinian eruptions and passive collapse events as the mechanisms of formation of martian pit chain craters. *J. Geophys. Res.*, (E3), 10.1029/2000JE001432.
- Scott, E.D., Wilson, L. & Head, J.W. (2002). Emplacement of giant radial dykes in the northern Tharsis region of Mars. *J. Geophys. Res.*, (E3), 10.1029/2000JE001431.
- Wilson, L. and P.J. Mouginis-Mark (2003a). The Phreatomagmatic Explosive Origin of Hrad Vallis, Mars. *J. Geophys. Res.* 108: 10.1029/2002JE001927.
- Wilson, L. and P.J. Mouginis-Mark (2003b). Phreato-magmatic dike-cryosphere interactions as the origin of small ridges north of Olympus Mons, Mars. *Icarus* 165: 242 - 252.

*Abstracts published:*

- Baloga, S.M., P.J. Mouginis-Mark, and L.S. Glaze (2001). Massive debris flows at Pavonis and Arsia Montes, Mars. Fall 2001 AGU Meeting, abstract # P31B-08
- Kallianpur, K. and P.J. Mouginis-Mark (2001). Slopes of Martian volcanoes. *Lunar Planet. Sci.* XXXII, abstract #1258.
- Mitchell, K.L. and L. Wilson (2001). Explosive volcanic eruptions on Mars: Misconceptions and new insights. *Lunar Planet. Sci.* XXXII, abstract #1190.
- Mouginis-Mark, P. J. Prodigious ash deposits near the summit of Arsia Mons volcano, Mars. *Lunar Planet. Sci.* XXXIII, abstract #1407.
- Mouginis-Mark, P.J. and K.J. Kallianpur (2002). Heights of Martian volcanoes and the geometry of their calderas from MOLA data. *Lunar Planet. Sci.* XXXIII, abstract #1409.
- Mouginis-Mark, P.J. Martian volcanoes seen in cross-section in Mars Orbiter Camera images. *Lunar Planet. Sci.* XXXII, abstract #1483.
- Mouginis-Mark, P.J., K. Kallianpur, G. Young, and L. Wilson (2000). Explosive eruptions on Hecates Tholus, Mars: Insights from Mars Global Surveyor data. Fall 2000 AGU meeting.
- Wilson, L. and J W Head (2001). The Consequences for Volcanic Eruption Styles on Mars of Shallow Interactions Between Magma and Volatiles. Fall 2001 AGU meeting, abstract # P31B-04.
- Wilson, L. and J.W. Head (2002). Volcanic eruption styles on Mars due to shallow interactions between magma and volatiles. *Lunar Planet. Sci.* XXXIII, abstract #1275.
- Wilson, L. and P.J. Mouginis-Mark (2001). Styles of phreatomagmatic activity adjacent to volcanic constructs on Mars. Spring 2001 AGU meeting, abstract # V42A-11.
- Wilson, L. and P.J. Mouginis-Mark (2001). Estimated volcanic eruption conditions during a large flank eruption on Elysium Mons, Mars, using Mars Global Surveyor data. *Lunar Planet. Sci.* XXXII, abstract #1259.

Wilson, L. and P.J. Mouginis-Mark (2002). The formation of Hrad Vallis, mars, and its associated deposits by an explosive sill-cryosphere interaction. Lunar Planet. Sci. XXXIII, abstract #1273.

### 3. Implications for Future Work

a) In our work on Hrad Vallis (Wilson and Mouginis-Mark, 2003a) we identified a "mud phase" of ejecta deposition associated with the earliest phase of explosive volcanism that we interpreted to be the result of sill intrusion into volatiles. Further analysis of this deposit is warranted because it is, to date, the only deposit that has been identified at the source area of an outflow channel on Mars, and thus may indicate unique characteristics of the substrate. Inspection of MOC data suggests that, if this explosive phase was continuous throughout the eruption or an early phase event, we should be able to see if the unit has been eroded by later water flow from the source (i.e., explosive only in early phase) or no erosion (i.e., continuous explosive activity). Investigation of this area is continuing under our current MDAP grant (NAG5-13323).

b) We identified large areas of the summit of Arsia Mons that may be ash deposits (Mouginis-Mark, 2002). Explosive volcanism on the Tharsis Montes had not been previously identified, and opens up the possibility of a greater range of eruption styles for these volcanoes. Our earlier work suggested that there could be spatial variations in deposit morphology as a function of elevation on the Tharsis volcanoes. Correlating MOC and THEMIS observations with the elevation data from MOLA, as well as looking at the other Tharsis volcanoes, may reveal systematic trends in the style(s) of volcanism. Again, we are conducting these follow-on investigations under our current MDAP grant.

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